Title of proposed experiment:

Study of the decay $\pi \to e\nu$

Name of group: PIENU

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Start of preparations: Summer in 2006

Date ready: Fall in 2006

Completion date: Fall in 2008

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
250 shifts	M9 or M13	unpolarized

Electron-muon universality in weak interactions has been tested at the 0.16 % level by the measurements of the branching ratio of the decays $\pi^+ \to e^+\nu$ and $\pi^+ \to \mu^+\nu$, $R_{e/\mu} = \frac{\Gamma(\pi\to e\nu)}{\Gamma(\pi\to\mu\nu)} = (1.2312\pm0.0037)\times10^{-4}$. Recent theoretical calculations have suggested the test could be further improved almost by an order of magnitude over the present level. Because of helicity suppression in the $\pi^+ \to e^+\nu$ decay by four orders of magnitude, the measurement of $R_{e/\mu}$ is extremely sensitive to a presence of pseudo-scaler couplings, which arise in many extensions of the standard model, such as those with charged Higgs particles, lepto-quarks and SUSY particles.

The time and energy spectra of positrons from the decays $\pi^+ \to e^+\nu$ ($T_{e^+} = 69.3$ MeV) and $\mu \to e\nu\overline{\nu}$ ($T_{e^+} = 0 - 52.3$ MeV) following the decay $\pi^+ \to \mu^+\nu$ ($\pi^+ \to \mu^+ \to e^+$ decay) will be measured using an inorganic-crystal detector array (TINA and surrounding CsI crystals) with a solid angle of 25 %. Simultaneous fitting of the time distributions of $\pi \to e\nu$ and $\pi \to \mu \to e$ decays provides the ratio of $\pi^+ \to e^+\nu$ decay and $\pi^+ \to \mu^+\nu$ decays. Small corrections will be applied for the $\pi^+ \to e^+\nu$ events hidden under the $\pi \to \mu \to e$ spectrum and for energy-dependent effects.

The event statistics will be improved over the previous experiments by a factor of 30 due to the larger solid angle and longer data taking period. Systematic uncertainties will also be reduced to 0.03 % levels using a carefully arranged counter geometry and extensive Monte Carlo calculations. The goal of the proposed experiment is to measure the branching ratio with precision of $< 0.1\%$.

Experimental area

M13 (production run) / M9 (test run)

Primary beam and target (energy, energy spread, intensity, pulse characteristics, emittance)

A 500 MeV, > 100 μA unpolarized proton beam is required. The production targets at T1 or T2 is a 1-cm thick beryllium (graphite) target.

Secondary channel M13 (production run) /M9 (test run)

Secondary beam (particle type, momentum range, momentum bite, solid angle, spot size, emmittance, intensity, beam purity, target, special characteristics)

The required π^+ beam momentum range is 70–85 MeV/c with a momentum bite of 1 %. The expected spot size is 1.5 cm $\times$ 1.5 cm at the stopping target. An optimum number of stopping π^+'s is $5 - 10 \times 10^4$ s^{-1}.

TRIUMF SUPPORT:

–Fabrication of the target and telescope counters.
–A temperature controlled tent for the CsI array.
–Design and fabrication of the mechanical support for the CsI array.
–750 cables between the experimental area and the electronics hut.
–Special electronics:
 –150 channels of CAMAC/VME type discriminators.
 –150 channels of 100-MHz waveform digitizers.
 –6 channels of 500MHz wave-form analyzers.
 –One 1-GHz TDC with a nonlinearity better than 0.01 %.
 –150 channels of HV's, and 6 channels of chamber HV's.
–"Deadtime-less" trigger and DAQ design.
–TINA
–Gas recycling system.
–Production of a 35-cm radius, x-y readout wire-chamber.
–A dry room for repacking of CsI and possibly re-canning of TINA.

Most items listed above have been requested to NSERC but some support from TRIUMF is necessary.

NON-TRIUMF SUPPORT

–An array of CsI crystals and their photo-multipliers (from BNL E949).

No unusual safety hazards are associated with this experiment. Standard precautions will be taken with the scintillation counter high voltages, and the chamber gases in the M13 area.

1 Scientific Justification

Electron-muon universality, within the context of the Standard Model (SM), refers to the fact that those charged leptons have identical electroweak gauge interactions. They differ only in their masses and couplings to the neutral physical Higgs scalar, a remnant of electroweak symmetry breaking and mass generation. In fact, a generalization of the universality concept would be that all chiral changing scalar (pseudoscalar) interactions should scale with particle masses.

As summarized in Table I, e-μ universality in the charged current mode has been studied with π, τ and W leptonic decays. The most stringent test of e-μ universality comes from a measurement of the branching ratio of the decays $\pi^+ \to e^+\nu$ and $\pi^+ \to \mu^+\nu$ followed closely by measurements of τ decay. Marciano [1] has pointed out that the branching ratios, $\frac{\Gamma(\pi\to e\nu)}{\Gamma(\pi\to\mu\nu)}$ and $\frac{\Gamma(K\to e\nu)}{\Gamma(K\to\mu\nu)}$, are sensitive to the longitudinal component of the W coupling (scalar and vector), while the others test the transverse component (vector).

Process	g_e/g_μ			ref.
π decay	0.9985	$\pm$	0.0016	[2,3]
K decay	0.994	$\pm$	0.022	[4,5]
τ decay	0.9999	$\pm$	0.0021	[6]
ν_e, ν_μ scattering	1.10	$\pm$	0.05	[7,8]
W decay	0.999	$\pm$	0.011	[6]

Table 1 A summary of e-μ universality tests.

In lowest order, the $\pi \to e\nu$ branching ratio $R^0_{e/\mu}$ is calculated to be

$$R^0_{e/\mu} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 = 1.28347 \times 10^{-4}. \quad (1)$$

Its smallness is a consequence of helicity suppression in the lowest order pseudoscalar weak decay amplitudes. Since the observed branching ratio includes the effect of physical and virtual photons, knowledge of radiative corrections to the branching ratio is important in order to extract the ratio of the coupling constants. Early calculations [11] for the radiative process assuming a point-like pion showed that the correction was of the order of $\delta = (3\alpha/\pi)\ln(m_e/m_\mu)$, which reduced the calculated branching ratio to $R^{th}_{e/\mu} = 1.233 \times 10^{-4}$. The major uncertainties of the calculations were in the divergences and pion-structure dependence. In the SM, electroweak radiative corrections to the $\Gamma(\pi \to l\bar{\nu}_l)$, $l = e, \mu$ decay rates are finite and calculable when expressed in terms of renormalized parameters. After including small structure dependent effects and the leading 2-loop logarithmic corrections one finds the SM prediction[1,12]:

$$R^{SM}_{e/\mu} = 1.2353(4) \times 10^{-4}, \quad (2)$$

where the error is very small but still quite conservative.

The prediction in (2) is to be compared with the most recent experimental results

$$R^{exp}_{e/\mu} = 1.2265 \pm 0.0034(stat) \pm 0.0044(syst) \times 10^{-4} \qquad TRIUMF[2], \text{ and} \quad (3)$$

$$R^{exp}_{e/\mu} \quad = \quad 1.2346 \pm 0.0035(stat) \pm 0.0036(syst) \times 10^{-4} \qquad PSI[3]. \tag{4}$$

Together, they give an average

$$R^{exp}_{e/\mu} = 1.231 \pm 0.004 \times 10^{-4} \qquad (Average). \tag{5}$$

The present proposal aims to improve the precision of $R^{exp}_{e/\mu}$ by about a factor of 5, thereby confronting the SM prediction to better than $\pm 0.1\%$. At that level, one could potentially uncover "new physics" beyond the SM via a deviation from expectations. Candidate examples of the "new physics" probed include heavy neutrino mixing with mixing angle ≥ 0.0005 as well as high scale four fermion operators due to excited gauge bosons (*e.g.* from extra dimensions), leptoquarks, compositeness or charged Higgs bosons.

Because of strong helicity-suppression in the $\pi \to e\nu$ decay, it is extremely sensitive to helicity-unsuppressed couplings such as the pseudo-scalar coupling. Since the pseudo-scalar contribution comes as an interference term with the dominant axial-vector term, the contribution is proportional to $1/m_H^2$, where m_H is the mass of a hypothetical particle—this is in contrast to $1/m_H^4$ dependence in lepton flavour violating decays. Ignoring small contributions from $\pi \to \mu\nu$ decay, with a presence of pseudoscalar interactions the deviation of the new branching ratio from the SM prediction can be parameterized as

$$1 - \frac{R^{New}_{e/\mu}}{R^{SM}_{e/\mu}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda^2_{eP}} \frac{m_\pi^2}{m_e(m_d + m_u)} \tag{6}$$

$$\sim (\frac{1TeV}{\Lambda_{eP}})^2 \times 10^3, \tag{7}$$

where Λ^2_{eP} is a mass scale of new pseudoscalar interaction in $\pi \to e\nu$ decay. This makes the measurement of a 0.1 % level of the $\pi \to e\nu$ branching ratio sensitive to the mass scales of 1000 TeV for pseudoscalar interactions. Scalar couplings arising from physics beyond the SM will also induce pseudo-scalar interaction through loop corrections, and in many cases the $\pi^+ \to e^+\nu$ branching ratio measurement provides substantially stronger limits than ones from direct β-decay searches [9]. In the case of R-parity violating SUSY, the exchange of various generations of squarks may lead to a non-universal contribution that results in a comparable deviation, and the measurement of $R_{e/\mu}$ places substantial constraints on the possible size of R-parity violating effects.[10]

2 Previous Measurements

The experiments at TRIUMF [2] and PSI [3], published in the early 90's, used inorganic crystals with energy resolution of ~ 5 % (FWHM for 70 MeV positrons) as the primary component of the detector, collecting $(1-2) \times 10^5$ $\pi \to e\nu$ events. The TRIUMF experiment employed the "traditional" method in which the time of positrons from the decays $\pi^+ \to e^+\nu$ ($T_{e^+} = 69.3$ MeV) and $\mu^+ \to e^+\nu\overline{\nu}$ ($T_{e^+} = 0 - 52.3$ MeV) following the decay $\pi^+ \to \mu^+\nu$ (the $\pi^+ \to \mu^+ \to e^+$ decay) were detected.

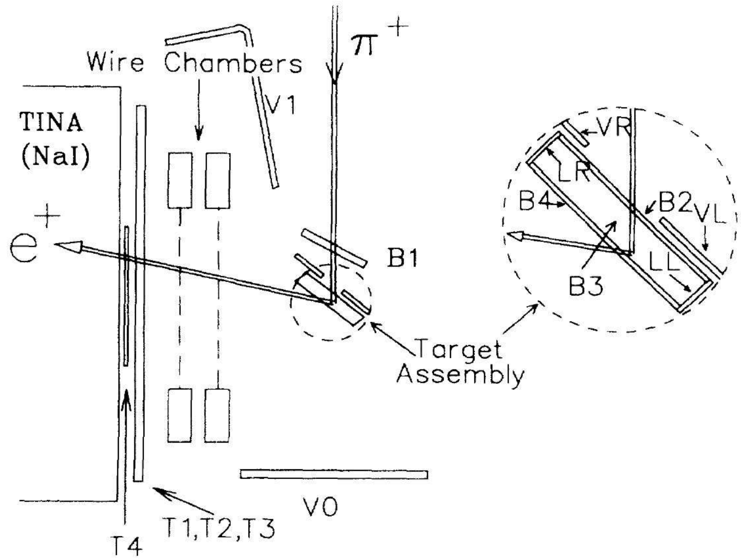

Fig. 1 Setup of the E248 experiment at TRIUMF

The time spectra of direct pion-decay products for $\pi^+ \to e^+\nu$ and $\pi^+ \to \mu^+\nu$ were used in the analysis of the PSI experiment —this made the PSI experiment insensitive to the pion lifetime but vulnerable to many uncertainties in the detector system, such as the acceptances for positrons and muons. Another major difference was in the methods of estimating the fraction of low-energy $\pi^+ \to e^+\nu$ (γ) decay events. The TRIUMF experiment obtained the tail correction empirically, while in the PSI experiment the amount of the low energy tail was estimated purely from Monte Carlo calculations.

The TRIUMF experiment[2] was carried out using a π^+ beam with the momentum $P = 83\pm1$ MeV/c. Figure 1 shows the setup. The incoming beam was stopped in a 1.2-cm-thick plastic-scintillator target at a rate of 7×10^4 s^{-1}. Thin plastic scintillators surrounding the target confined the stopping region of the pions, and contained the muons from the $\pi^+ \to \mu^+\nu$ decay (1.4 mm in range). The positrons from the decays of stopped pions in the target were detected at 90° to the beam by a 2.9 % solid-angle telescope consisting of two planar wire chambers, three thin plastic scintillators, and a 46-cm-diameter × 51-cm-long NaI(Tl) crystal, TINA. A positron energy spectrum in the time region 5–30 ns is shown in Fig. 2. The raw branching ratio was determined by simultaneously fitting, to the expected time evolution, the measured decay-time spectra (Fig. 2 right) for positron events above and below the threshold energy at 56.4 MeV, which divides the energy spectrum measured by TINA into the $\pi \to e\nu$ and $\pi \to \mu \to e$ decay regions, respectively.

In order to empirically determine the low-energy fraction of the $\pi \to e\nu$ events below the cut-off energy 56.4 MeV, the dominant $\pi \to \mu \to e$ component was suppressed by using energy and pulse-shape information from the target counter as well as decay time information [13]; for $\pi \to e\nu$ decay events, the total energy measurement in the target included the kinetic energy of the stopping pion plus a small contribution from the exiting decay positron, while for $\pi \to \mu \to e$ decay events there was an additional 4-MeV pulse from the kinetic energy of the decay muon. Fig. 3 shows a scatter plot of the target

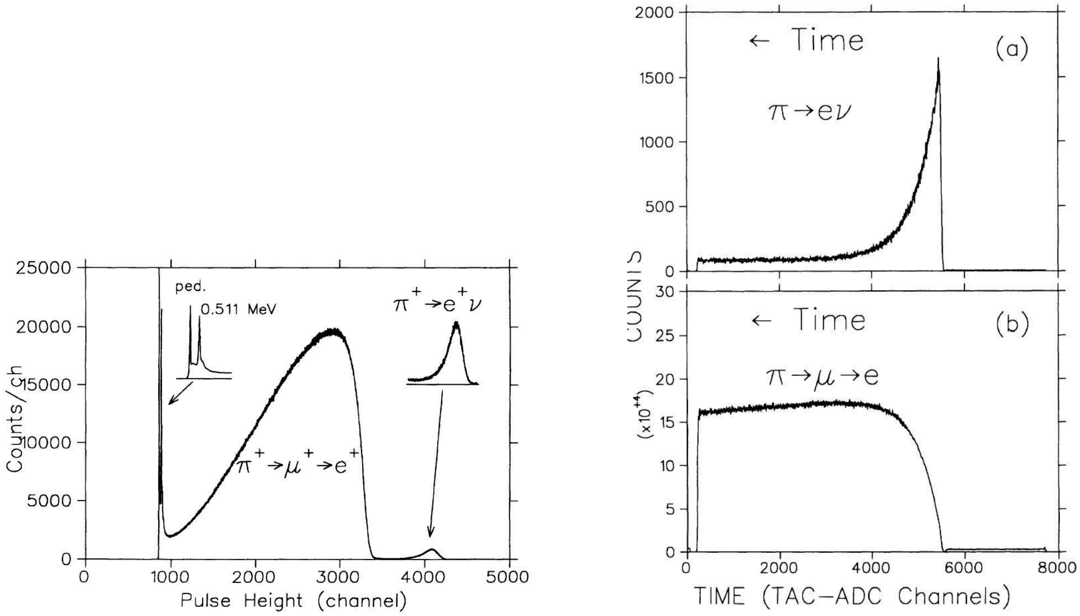

Fig. 2 Left: Energy spectrum of e^+'s in the early time window. Right: Time spectra for events in the (a) $\pi^+ \to e^+\nu$ and (b) $\pi^+ \to \mu^+ \to e^+$ energy regions.

energy observed with a wide-gate ADC vs the early part of the pulse observed with a narrow-gate ADC. The lines show the cuts to select $\pi \to e\nu$ events for the tail analysis. A total suppression factor of 10^5 for $\pi \to \mu \to e$ events was obtained as shown in Fig. 3. The residual background of $\pi \to \mu \to e$ events in the positron energy spectrum, due mostly to decay-in-flight pions, was subtracted using the energy spectrum of events occurring ~8 pion lifetimes after the pion stop. The overall tail correction 1.93 ± 0.25 % was obtained after adding a 0.4 % correction for the bias that was introduced by the selection criteria of the $\pi \to e\nu$ events. The uncertainty was limited by statistics.

Monte Carlo (MC) calculations were used to correct for systematic effects related to positron annihilation-in-flight, multiple Coulomb scattering leading to pathological trig-

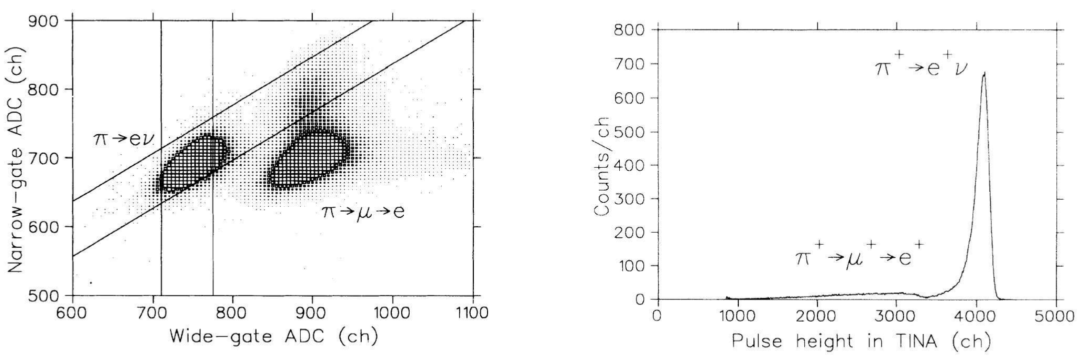

Fig. 3 Left:Target energy observed with wide-gate ADC vs narrow-gate ADC. Right: Energy spectrum of e^+'s after background suppression.

gers, and the fraction of very low-energy $\pi \to \mu \to e$ positrons (below 5 MeV) lost in the trigger. The combined correction from the MC studies was 0.27 ± 0.11 %.

The corrections applied to the raw branching ratio are summarized in Table II. The final result based on 1.7×10^5 $\pi \to e\nu$ events was $R^{exp}_{e/\mu} = (1.2265 \pm 0.0034(stat) \pm 0.0044(sys)) \times 10^{-4}$.

Correction items	corrections(%)		errors
Tail correction	1.93	$\pm$	0.25
Monte Carlo	0.27	$\pm$	0.11
π lifetime	0.00	$\pm$	0.09
Others	0.05	$\pm$	0.11

Table 2 Correction summary of the TRIUMF experiment.

3 Proposed experiment

The concept of the new experiment is based on the previous TRIUMF experiment (E248). The branching ratio $R^{exp}_{e/\mu}$ will be obtained from the ratio of positron yields from the $\pi^+ \to e^+\nu$ decay ($E_{e^+} = 69.3$ MeV) and from the $\pi^+ \to \mu^+ \to e^+$ chain decay ($E_{e^+} = 0$–52.3 MeV). By measuring positrons from the decays $\pi^+ \to e^+\nu$ and $\mu^+ \to e^+\nu\overline{\nu}$ following the decay $\pi^+ \to \mu^+\nu$, many normalization factors, such as the solid angle of positron detection, cancel in the first order, and only small energy-dependent effects, such as those for multiple Coulomb scattering and positron annihilation, need to be corrected for.

Figure 4 shows the experimental setup, in which B and T indicate beam- and telescope-counters, respectively. A 75 MeV/c π^+ beam will be identified by B1 and B2, and stopped in a target consisting of an array of plastic scintillators (a 2-cm diameter, 1-cm thick stopping counter sandwiched by two 2-mm thick disc counters). Fine tracking near the target will be provided by two double-sided silicon-strip counters located immediate upstream and downstream of the target assembly. In order to keep a low background level arising from old muons in the target region and to minimize potential distortions in the time spectrum due to pile-up, the beam rate will be kept around $\sim 5 - 10 \times 10^4$ pions/s. The telescope counters T1–3 are 2 mm thick discs, covering the front side of TINA. A 35-cm diameter dual-coordinate wire chamber (WC3) is located next to the T3 counter and provides position information of the positron for evaluation of the shower leakage effect and correction of the path length in the T counters for dE/dX measurements. The solid angle of the telescope is 25 %. The "Ring" in the figure is a cylinder of at least 10-cm thick, 2×25-cm long CsI counters to capture shower leakage from TINA. According to MC calculations with the proposed geometry, the fraction of the low-energy tail of $\pi \to e\nu$ events is expected to be similar to that of the E248 experiment. The improvement in statistics is therefore expected to come from a larger solid angle by an order of magnitude and a longer running period.

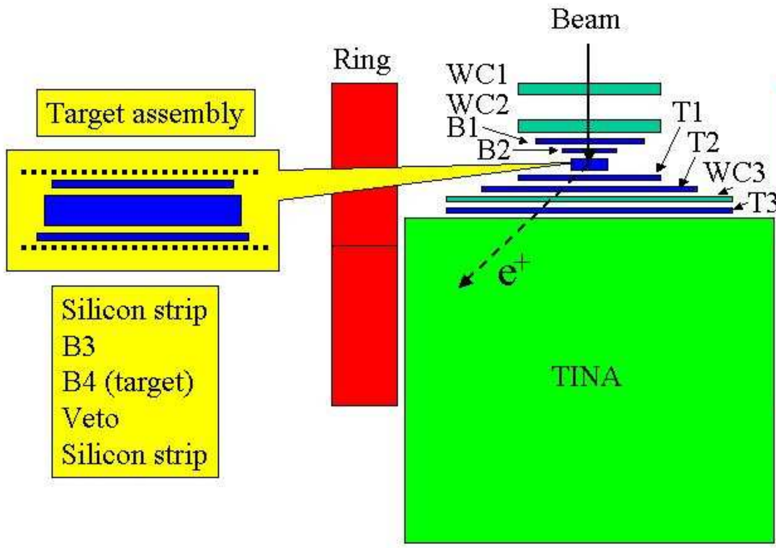

Fig. 4 Proposed setup

There will be at least three types of triggers; events in the early time window (3–25 ns) for the tail correction measurement, high energy (above 55 MeV) events for $\pi \to e\nu$ counting, and pre-scaled events for $\pi \to \mu \to e$ counting, corresponding to the expected rates of 300, 100 and 600 Hz, respectively. Assuming all detectors are read out by 500 MHz (plastic counters) or 100 MHz (NaI and CsI) wave-form-digitizers and fast TDC's based on the ATLAS AMT-3 chip, the expected event size is 3000 bytes with zero suppression, but with more inteligence in the DAQ system the data size will be reduced to half by keeping only time and pulse height information for out-of-time pulses.

In the analysis, the measured positron spectrum will be divided into low-energy ($\pi \to \mu \to e$) and high-energy ($\pi \to e\nu$) regions slightly above the end point of the $\pi^+ \to \mu^+ \to e^+$ decay. Simultaneous fitting of the time distributions of low- and high-energy regions provides the yields of $\pi^+ \to e^+\nu$ decay and $\pi^+ \to \mu^+ \to e^+$ decay, respectively. One of the major uncertainties of the previous experiments was due to the low-energy tail of $\pi^+ \to e^+\nu(\gamma)$ events that was buried under the large $\pi^+ \to \mu^+ \to e^+$ population. In the present experiment, the same suppression technique as E248 will be used to deduce the low-energy tail correction.

4 Expected Precision

With a 25 % detection solid angle and a beam rate of 7×10^4 $\pi^+\mathrm{s}^{-1}$, a total of 2×10^7 $\pi \to e\nu$ events will be accumulated in 100 days. Assuming a 30 % analysis acceptance, 5×10^6 events will be used for the $\pi \to e\nu$ branching ratio determination. With less background due to pile-up, the improvement factor over the previous experiment is about 30, resulting in the statistical uncertainty of 0.05 % in branching ratio.

The dominant uncertainty in the TRIUMF experiment was in the knowledge of the low-energy tail which was limited by statistics. Having a larger solid-angle detector not only reduces the statistical uncertainty of the $\pi^+ \to e^+\nu$ sample, but also results in the same improvement factor for the tail correction. The major low-energy background in the background-suppressed spectrum came from in-flight decays of pions near the target; these events had the same signature as that of $\pi^+ \to e^+\nu$ decays in the target. A better beam momentum bite and better dE/dX measurements at the entrance of the target would result in an additional background suppression factor of two, contributing to further improvement. An overall improvement factor of $> 5.$ in the uncertainty of the tail correction is therefore expected. The uncertainty arising from the low energy tail can be as small as 0.03 %.

The second largest systematic uncertainty came from the energy dependence of multiple-Coulomb- and Bhabha-scattering cross sections; there is a slight difference between the numbers of events going out (coming in) from (to) the defined region of the solid angle. This energy dependent effect is roughly proportional to the ratio of the circumference of the solid-angle defining counter and the solid angle. A larger solid angle (25 % compared to 3 % in E248) is expected to reduce the uncertainty of this correction by ~ 3 from the previous level of 0.1 %. With the progress of MC simulations and more computing power, we expect further improvement may be possible.

One of the important corrections is positron energy dependence of the time-zero measurement which had an uncertainty of 0.08 % in E248. This was limited by the statistics of calibration data in the previous experiment because the acceptable uncertainty level of each correction was of the order of 0.1 % and better statistical precision was not necessary; during the previous experiment, only a few hours were spent for this calibration. The contribution from the pion lifetime uncertainty has been reduced to the level of 0.02 % by new measurements. [14]

Sources	Estimated uncertainties (%)
Statistical error	0.05
Tail correction	0.03
Acceptance difference	0.03
Pion lifetime	0.02
Others	0.03
Estimated total systematic error	0.06

Table 3 Expected uncertainties.

As summarized in Table III, the proposed experiment will accumulate 30 times more $\pi^+ \to e^+\nu$ decay events than E248, and all contributing uncertainties are to be reduced at least by a factor of three. These improvements will lead to an expected precision of the branching ratio of the decays $\pi^+ \to e^+\nu$ and $\pi^+ \to \mu^+\nu$ to be better than 0.1 %, which corresponds to a 0.05 % uncertainty in the ratio of the coupling constants g_e/g_μ. Although the experimental equipment and method described here allow us to achieve the above goal, further possibilities of improvements are being investigated.

5 Readiness

Six months after the arrival of the CsI crystals. The estimated start time is in November, 2006.

6 Beam Time required

We propose a three-stage experiment with several months of break between the phase.

Test experiment (M9)			
	Setup time	2	months
	Data taking	1	month
Test setup (M13)			
	Setup time	2	months
	Data taking	1	month
Data taking			
	Setup time	1	month
	Tune up	1	month
	Data taking	6	months

7 Data Analysis

Based on the E248 and TWIST experiments, we expect 300 SDLT tapes. The computing power requirement is very similar to that of the TWIST experiment.

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